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Abstract. The method earlier used for the *fo*F2 long-term trends analysis is applied to reveal hmF2 long-term trends at 27 ionosonde stations in the European and Asian longitudinal sectors. Observed M(3000)F2 data for the last 3 solar cycles are used to derive hmF2 trends. The majority of the studied stations show significant hmF2 linear trends with a confidence level of at least 95% for the period after 1965, with most of these trends being positive. No systematic variation of the trend magnitude with latitude is revealed, but some longitudinal effect does take place. The proposed geomagnetic storm concept to explain hmF2 long-term trends proceeds from a natural origin of the trends rather than an artificial one related to the thermosphere cooling due to the greenhouse effect.

Key words. Ionosphere (ionosphere-atmosphere interaction)

1 Introduction

There is a permanent interest in the problem of global changes in the terrestrial atmosphere due to an antropogenic impact. Most of the discussion of this problem has focused on the troposphere and stratosphere, which are of immediate human and economic concern. But long-term changes in the thermosphere and ionosphere should also be studied seriously not only for their possible practical importance for the ionospheric HF radio-wave propagation, but also for their potential use as indicators of changes at lower heights. During recent years several attempts have been made to analyse various sets of long period observations in order to reveal the long-term effects in various ionospheric parameters (Givishvili and Leshchenko, 1994, 1995; Givishvili et al., 1995; Ulich and Turunen, 1997, Rishbeth, 1997; Jarvis et al., 1998; Bremer, 1992, 1998; Danilov 1997, 1998; Upadhyay and Mahajan, 1998; Danilov and Mikhailov 1998, 1999; Sharma et al., 1999; Foppiano et al. 1999; Mikhailov and Marin 2000; Deminov et al., 2000). But no final concept has been developed yet. Based on the model calculations of Roble and Dickinson (1989) who predicted a marked cooling of the mesosphere and thermosphere due to an enhancement of the atmospheric greenhouse gases, Rishbeth (1990) and Rishbeth and Roble (1992) predicted a lowering of the F2-layer height. Assuming these predictions, some researchers have been trying to explain the observed long-term trends in the ionospheric parameters as an indication of this greenhouse effect in the mesosphere and thermosphere (Bremer, 1992; Givishvili and Leshchenko, 1994; Ulich and Turunen, 1997; Jarvis et al., 1998; Upadhyai and Mahajan, 1998). Satellite drag observations by Keating et al. (2000) revealed a 10% decrease in neutral density at 350 km for the 20 year (1976–1996) period which seems to confirm the thermosphere cooling due to the greenhouse effect. On the other hand, the results of analysis by Bremer (1998) over many European ionosonde stations, Upadhyay and Mahajan (1998) over the world-wide ionosonde network, as well as the hmF2 trend analysis for the Southern Hemisphere ionosonde stations by Jarvis et al. (1998) and Foppiano et al. (1999) have shown that the F2-layer parameter trends turn out to be different both in sign and magnitude for different stations and this can hardly be reconciled with the greenhouse hypothesis. Therefore, Upadhyay and Mahajan (1998) concluded that the analysed data do not provide a definitive evidence of any global long-term trend in the ionosphere. Jarvis et al. (1998) relating the revealed hmF2 trends with the greenhouse effect, nevertheless stress that other explanations cannot be ruled out.

It must be pointed out that different authors use different approaches to extract long-term trends from the ionospheric observations and the success of analysis depends to a great extent on the method used. F2-layer ionospheric parameters strongly depend on solar and geomagnetic activity. These effects make it difficult to detect long-term trends because these changes are relatively small compared to the solar and geomagnetic ones. The useful “signal” is very small and the “background” is very noisy, so special methods are required

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Table 1. Years of solar minimum and maximum used in the analysis

Years of solar minimum	Years of solar maximum
1943, 1944	1947, 1948, 1949
1953, 1954	1957, 1958, 1959
1964, 1965	1968, 1969, 1970
1975, 1976	1979, 1980, 1981
1985, 1986	1989, 1990, 1991

to reveal significant trends from the ionosonde observations. An approach being developed by Danilov and Mikhailov (1998, 1999) and Mikhailov and Marin (2000) has allowed us to find systematic variations of the *fo*F2 trend magnitude with geomagnetic (invariant) latitude and local time. The application of this approach to *fo*F2 trend analysis resulted in a new geomagnetic control concept based on the contemporary understanding of the F2-layer storm mechanisms (Mikhailov and Marin, 2000). Since hmF2 and NmF2 are related by the mechanism of the F2-layer formation, any hypothesis of the F2-layer parameter trends should explain the observed trends of both parameters simultaneously. Therefore, if the F2-layer trends are primarily controlled by the geomagnetic activity, the hmF2 long-term trends should also demonstrate corresponding temporal and spatial variation. The aim of this paper is to study hmF2 long-term trends in order to check if the results may be reconciled with the proposed geomagnetic control hypothesis.

2 Data and method

The height of the F2 layer (hmF2) data used in our analysis has been prepared according to the following steps:

1. Monthly M(3000)F2 medians on the analysed ionosonde stations were obtained from WDC-C at the Rutherford Appleton Laboratory (Chilton, UK) and from NGDC (Boulder, USA) to derive hmF2 values.

2. As we apply 12 month running mean smoothing to the hmF2 values (see below the first point of the method applied to extract the trends), gaps in the initial M(3000)F2 observations have to be filled in. This is done by using the monthly median MQMF2 model by Mikhailov et al. (1996), which is based on the M(3000)F2 third-degree polynomial regression with the sunspot number R_{12}. The regression is calculated for each station, with 24 moments of UT and 12 months. The initial M(3000)F2 monthly medians are converted to solar local time (SLT) using spline-interpolation.

3. The Shimazaki (1955) formula was used to derive hmF2 from M(3000)F2 hmF2 = [1490/M(3000)F2]–176.

The approach to reveal the *fo*F2 layer parameter trends is described in detail by Danilov and Mikhailov (1998, 1999) and Mikhailov and Marin (2000), so only the main points of the method applied to the hmF2 trend analysis are summarised below:

1. A 12 month running mean hmF2 rather than just monthly median hourly values are used in the analysis. The procedure of 12 month smoothing is the same used to obtain the 12 month running mean sunspot numbers R_{12} (CCIR, 1988). This is an important point not used by other researchers as it strongly decreases the scatter in observed hmF2 data. The use of 12 month running mean values does not eliminate annual variations but only smoothes them.

2. Relative deviations of the observed hmF2 values from some model are analysed

$$\delta hm\mathrm{F2} = (hm\mathrm{F2}_{\mathrm{obs}} - hm\mathrm{F2}_{\mathrm{mod}})/hm\mathrm{F2}_{\mathrm{mod}} \quad (1)$$

where $hm\mathrm{F2}_{\mathrm{mod}}$ is a third-degree polynomial regression with the R_{12} index. Other researchers (Givishvili and Leshchenko, 1994, 1995; Bremer, 1998; Upadhyay and Mahajan, 1998, Jarvis et al., 1998) considered absolute deviations rather than relative ones. The use of relative deviations allows us to combine values for different months to obtain the annual mean value analysed in our method.

We have calculated hmF2 trends using two models: a regression with R_{12} (Model 1) and a regression with a combination (R_{12} + 12 month running mean Ap index). The latter is done as an attempt to exclude the dependence on geomagnetic activity.

$$hm\mathrm{F2}_{\mathrm{mod1}} = a + bR_{12} + cR_{12}^2 + dR_{12}^3 \quad \text{(Model 1)}$$
$$hm\mathrm{F2}_{\mathrm{mod2}} = a + bR_{12} + cR_{12}^2 + dR_{12}^3 + eAp_{12} \quad \text{(Model 2)}$$

All the coefficients are calculated for each station, month, and SLT moment with the least squares method.

3. Linear trends (slope K) are estimated according to a linear δhmF2 regression with the year (δhmF2 = a + K year) for selected hours and months. As annual hmF2 variations (especially 12 month running mean values) are small, the annual variation of the hmF2 trends are rather small as well for all SLT moments. Such seasonal variations of the trends for 0, 6, 12 and 18 SLT are shown for several stations in Fig. 1 as an example. Therefore, only annual mean δhmF2 values at fixed hours are used to find annual mean trends.

4. The test of significance for the linear trend (K parameter) is made using the Fisher's F criterion (Pollard, 1977)

$$F = r^2(N-2)/(1-r^2),$$

where r is the correlation coefficient between the annual mean δhmF2 values and the year after Eq. (1), and N is the number of pairs considered. A 95% confidence level is applied in the paper.

5. To compare hmF2 linear trends at different stations, the same time period 1965–1991 is analysed. This is done to avoid the influence of different (falling/rising) periods in the long-term geomagnetic activity variations on the trend magnitude as well as for a comparison of *fo*F2 trends obtained for the same period (Mikhailov and Marin, 2000).

6. We use two selections of years in our analysis to reveal hmF2 trends: all years and then only years around solar cycle maximum and minimum (Table 1) to check if the selection of years makes a difference as it did with the *fo*F2 trends. (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000).

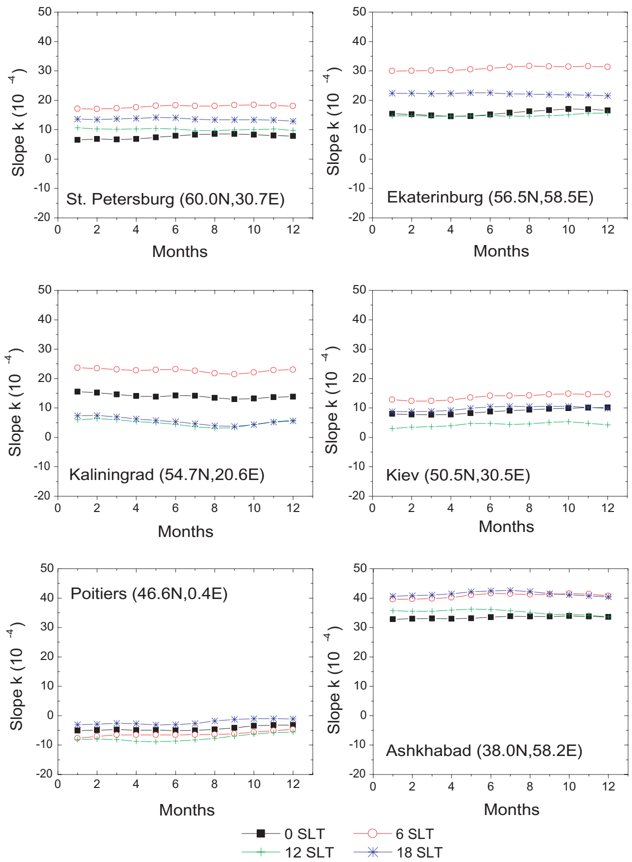

Fig. 1. Seasonal variation of the *hm*F2 trends at 6 European ionosonde stations and 4 moments of SLT. Regression of *hm*F2 with R_{12} (Model 1) is used.

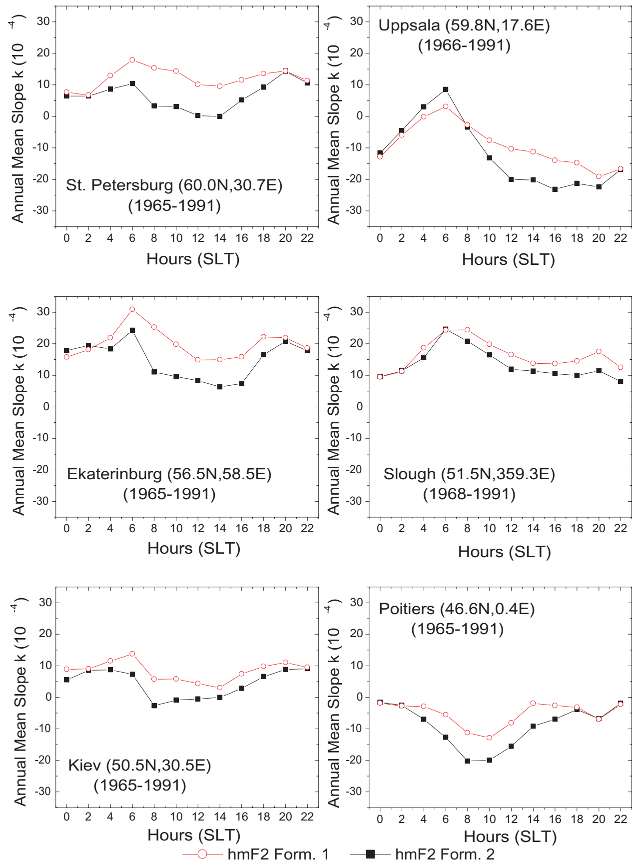

Fig. 2. Diurnal variation of the *hm*F2 trends when the Shimazaki (Formula 1) and the Dudeney (Formula 2) formulas were used to derive *hm*F2 from $M(3000)$F2.

3 *hm*F2 formula selection

In searching for the *hm*F2 trends it should be taken into account that *hm*F2 values are not directly scaled from ionograms as are other ionospheric parameters. A practical approach to derive *hm*F2 values is to use empirical formulas that link *hm*F2 to the MUF factor, $M(3000)$F2. Therefore, some investigations have been made in order to analyse the dependence of the results on the formula used. Bremer (1992) compared the *hm*F2 trends for the Juliusruh ionosonde station using four different methods to derive *hm*F2 (Shimazaki,1955; Bradley and Dudeney,1973; Dudeney, 1974; and Bilitza et al., 1979). He found that the choice of the formula was not critical for the derived trends. However, Ulich (2000) analysed several ionosonde stations showing that *hm*F2 trends may be different both in sign and magnitude depending on the formula used to derive *hm*F2.

Therefore, we have compared *hm*F2 trends for several European stations using the Shimazaki (1955) formula (Formula 1) and the Dudeney (1978) formula (Formula 2). The latter one is more accurate as it includes the dependence on the *fo*F2/*fo*E ratio:

$$hm\mathrm{F2} = (1490 M_F)/(M_3 + \Delta M) - 176$$

with

$$M_F = M_3\{[(0.0196 M_3^2 + 1)/(1.2967 M_3^2 - 1)]\}^{1/2}$$
$$M_3 = M(3000)\mathrm{F2}$$

and

$$\Delta M = 0.253/(r - 1.215) - 0.012$$
$$r = fo\mathrm{F2}/fo\mathrm{E}.$$

The results of such a comparison for St. Petersburg, Uppsala, Ekaterinburg, Slough, Kiev and Poitiers are shown in Fig. 2. All analysed stations demonstrate a systematic behaviour of the trends when both formulas are applied; the trend magnitude tending slightly to decrease when the effect of the underlying layer is taken into account by the ratio *fo*F2/*fo*E (Formula 2). The differences in the trend magnitude are not very large and they depend on the local time. Both formulas give close results during nighttime hours when *fo*E is small, but the difference increases during daytime hours when the E-layer contribution increases. Therefore, it should be kept in mind that *hm*F2 trend results are not as reliable as *fo*F2 ones because *hm*F2 values are inferred from $M(3000)$F2 by using some empirical formulas which insert

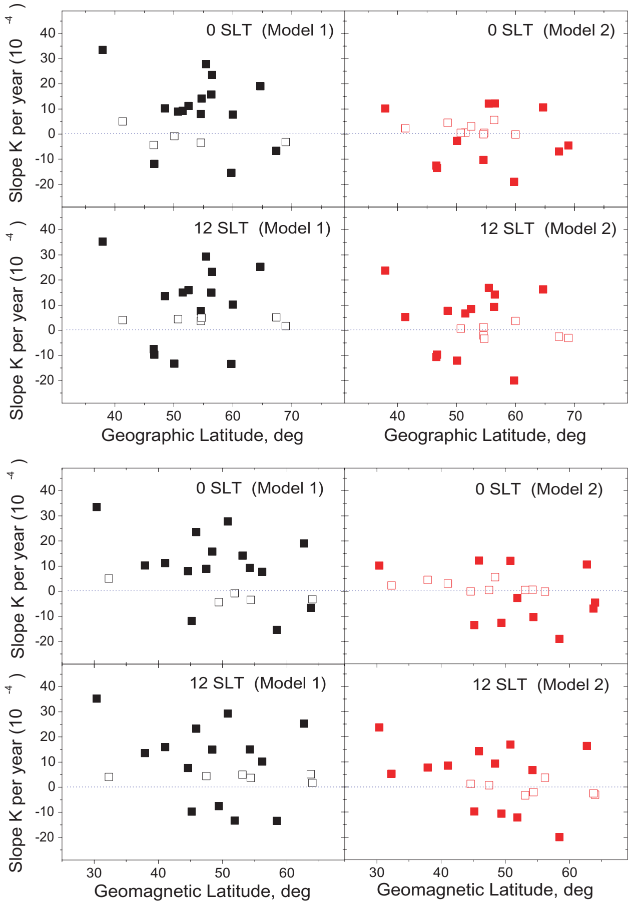

Fig. 3. A dependence of the *hm*F2 trend magnitude on geographic (top panel) and geomagnetic (bottom panel) latitude for two models, 00 and 12 SLT. Filled in symbols correspond to significant trends at a 95% confidence level. Note the absence of any pronounced dependence.

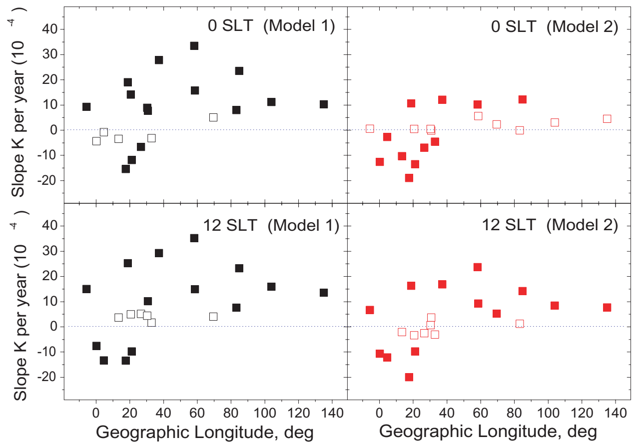

Fig. 4. Same as Fig. 3 but for the dependence on geographic longitude. Note some longitudinal effect with negative trends at western European stations.

an additional noise to the analysed *hm*F2 values. There are some problems with the use of formula (2). It includes the *fo*F2/*fo*E ratio, which should itself demonstrate long-term variations that distort the sought *hm*F2 trend. In addition, *fo*E values used in the formula (2) are not available at many stations during nighttime hours. Therefore, the simple formula by Shimazaki (1955) has been chosen for our analysis. This allowed us to analyse a greater number of ionosonde stations. In this context it should be mentioned that the use of model *fo*E values instead of absent *fo*E observations (Upadhyai and Mahajan, 1998) should distort the *hm*F2 trends as *fo*E itself demonstrates a long-term trend (Givishvili and Leshchenko, 1995; Bremer, 1998) which is not reflected by an empirical model such as IRI-90.

4 Calculated *hm*F2 trends

Ground-based ionosonde observations on 27 Eurasian stations located in the 37° N – 69° N and 5.6° W – 136° E sector are used in this study. The list of the stations is given in Table 2. The observations from most of them are seen to overlap the analysed period of 1965–1991, which corresponds to the period of increasing geomagnetic activity. Moreover, this time period is the richest, with observations over the worldwide ionosonde network.

The calculated *hm*F2 linear trends for four SLT moments (0, 6, 12 and 18) and two models are shown in Table 2. An inclusion of the dependence on Ap_{12} to the regression (Model 2) makes the trends more negative, while Model 1 provides more positive trend magnitudes. Mikhailov and Marin (2000) found the opposite effect of taking into account the dependence on the Ap index for the *fo*F2 trends which were more positive in the latter case.

Most of the stations listed in Table 2 show significant trends. The number of stations with significant trends (negative and positive) for four SLT moments and two models is summarised in Table 3. Most of them are seen to be positive even when the Ap index is included to the regression (Model 2). The only exception is for the 00 SLT (Model 2) case when the numbers of positive and negative significant trends are nearly the same. Therefore, the majority of the significant *hm*F2 trends are positive regardless of the model used. This is an important result of our analysis, which gives a clue for further physical interpretation.

Using the results given in Table 2, spatial (both latitudinal and longitudinal) variations of the *hm*F2 trends have been analysed. The slopes K at 00 and 12 SLT for the stations with observations available for the whole period 1965–1991 are plotted versus latitude (geomagnetic and geographic) and geographic longitude in Figs. 3 and 4, respectively. Regressions of *hm*F2 with R_{12} (Model 1) and with $R_{12} + Ap_{12}$ (Model 2) are used in both figures for a comparison. The scatter of the slope K at the analysed stations is seen to be smaller when the Ap_{12} index is included to the regression (Model 2). The calculated trends are seen to demonstrate no latitudinal dependence (Fig. 3) regardless of whether geographic or geomagnetic latitude is used, while a pronounced

Table 2. Ionosonde stations and calculated annual mean slope K (in 10^{-4} units) for the period 1965–1991. Regression of hmF2 with R_{12} (Model 1) and with $R_{12} + Ap_{12}$ (Model 2), and all years in the indicated period are used to obtain hmF2 linear trends. Significant trends at a confidence level of 95% are denoted by an "s" after the value

STATION	Lat. Geomag.	Lat. Geograp.	Long. Geograp.	0 SLT Model 1	0 SLT Model 2	6 SLT Model 1	6 SLT Model 2	12 SLT Model 1	12 SLT Model 2	18 SLT Model 1	18 SLT Model 2	Analysed Years
MURMANSK	64	69	33	−3.23	−4.63 s	3.48	−1.60	1.66	−3.09	3.43	−0.10	1965–91
SODANKYLA	63.73	67.4	26.6	−6.71 s	−6.94 s	8.24 s	1.50	5.08	−2.58	1.04	−3.26	1965–91
LYCKSELE	62.7	64.7	18.8	18.98 s	10.62 s	24.26 s	16.65 s	25.22 s	16.29 s	22.41 s	15.95 s	1965–91
ARKHANGELSK	58.7	64.6	40.5	−2.36	−5.31	8.95 s	6.15 s	4.77	−0.28	15.08 s	11.43 s	1970–89
UPPSALA	58.44	59.8	17.6	−15.49 s	−19.06 s	−0.11	−7.29 s	−13.42 s	−20.08 s	−19.85 s	−23.6 s	1965–91
ST PETERSBURG	56.17	60	30.7	7.64 s	−0.23	17.87 s	8.28 s	10.12 s	3.67	13.54 s	7.05	1965–91
JULIUSRUH	54.4	54.6	13.4	−3.48	−10.38 s	2.67	−4.42 s	3.63	−2.08	−0.19	−4.69 s	1965–91
SLOUGH	54.25	51.5	359.4	9.19 s	0.51	23.78 s	11.92 s	15.00 s	6.64 s	15.66 s	7.55 s	1965–91
KALININGRAD	53.1	54.7	20.6	14.06 s	0.44	22.75 s	9.23 s	4.91	−3.36	5.55	−1.91	1965–91
DOURBES	51.89	50.1	4.6	−0.86	−2.77 s	−2.71	−2.89 s	−13.36 s	−12.14 s	−23.75 s	−12.95 s	1965–91
YAKUTSK	51.2	62	129.6	19.55 s	11.16 s	22.66 s	12.58 s	15.96 s	6.93 s	18.37 s	9.92 s	1965–90
TUNGUSKA	50.9	61.6	90	9.7 s	2.53	4.64	0.64	16.64 s	9.15 s	12.77 s	6.95 s	1969–91
MOSCOW	50.82	55.5	37.3	27.8 s	12.07 s	31.87 s	18.19 s	29.26 s	16.82 s	31.18 s	18.12 s	1965–91
MAGADAN	50.75	60	151	9.29 s	2.15	9.02	0.35	−9.52 s	−14.2 s	3.19	2.90	1969–91
GORKY	50.29	56.15	44.28	0.69	−3.34	8.77 s	4.95	15.47 s	8.03 s	14.58 s	9.67 s	1965–88
POITIERS	49.4	46.6	0.3	−4.43	−12.63 s	−6.09 s	−12.9 s	−7.59 s	−10.74 s	−2.19	−5.75	1965–91
EKATERINBURG	48.42	56.4	58.6	15.75 s	5.57	30.87 s	19.6 s	14.87 s	9.21 s	22.15 s	14.61 s	1965–91
KIEV	47.5	50.72	30.3	8.89 s	0.41	13.75 s	5.37	4.35	0.64	9.82 s	4.93	1965–91
TOMSK	45.92	56.5	84.9	23.45 s	12.17 s	22.48 s	11.17 s	23.17 s	14.19 s	21.26 s	12.64 s	1965–91
BEKESCSABA	45.2	46.7	21.2	−11.94 s	−13.54 s	−3.77	−6.61 s	−9.8 s	−9.84 s	−9.39 s	−8.73 s	1965–91
NOVOSIBIRSK	44.61	54.6	83.2	7.96 s	−0.06	8.17 s	−0.15	7.59 s	1.17	6.2 s	0.28	1965–91
IRKUTSK	41.06	52.5	104	11.13 s	2.96	17.43 s	7.68 s	15.92 s	8.41 s	16.62 s	9.03 s	1965–91
KHABAROVSK	37.91	48.5	135.1	10.27 s	4.50	22.89 s	7.67	13.48 s	7.69 s	14.63 s	7.88 s	1965–91
NOVOKAZILINSK	37.6	45.77	62.12	1.44	−5.12	15.07 s	5.19	−0.97	−7.44	6.39	2.17	1965–88
ALMA ATA	33.42	43.2	76.9	12.51 s	5.64 s	28.27 s	20.84 s	18.77 s	16.31 s	22.98 s	19.55 s	1965–88
TASHKENT	32.3	41.33	69.62	4.99	2.29	10.98 s	6.51	3.97	5.17 s	9.37 s	8.01 s	1965–91
ASHKHABAD	30.39	37.9	58.3	33.41 s	10.16 s	40.78 s	22.89 s	35.22 s	23.7 s	41.44 s	23.23 s	1965–91

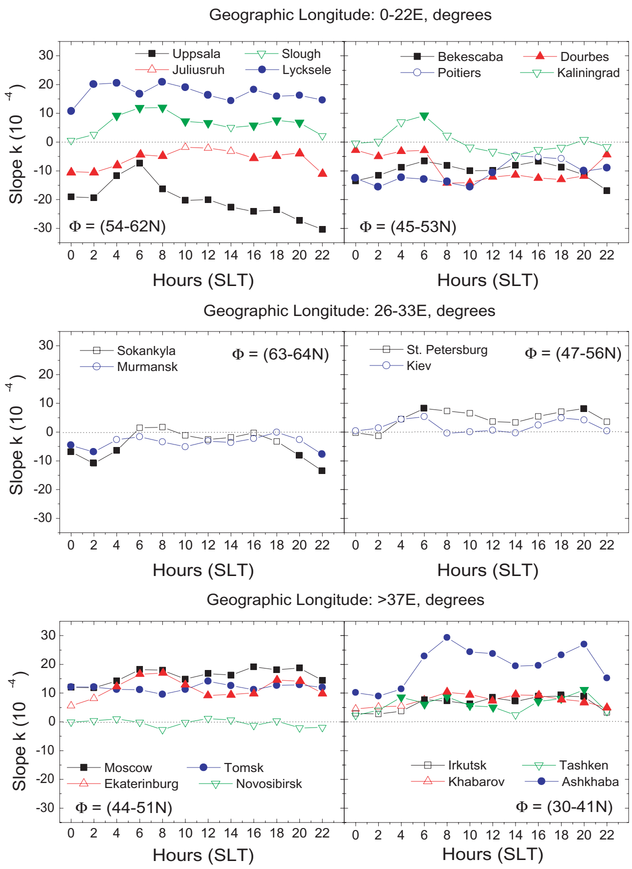

Fig. 5. Diurnal variation of the *hm*F2 trends in three longitudinal sectors. Regression of *hm*F2 with $R_{12} + Ap_{12}$ (Model 2) was used. Filled in symbols correspond to significant trends at a 95% confidence level. The interval of geomagnetic latitudes Φ where stations are located is given in the plots.

latitudinal dependence was revealed for the *fo*F2 trends (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000). This is another interesting result of our analysis which should be reconciled with the previous conclusions on the *fo*F2 trends. On the other hand, some longitudinal effect is seen in Fig. 4. The trends have a tendency to have different signs in the West European and in the East European/Asian longitudinal sectors.

All negative trends are observed at the stations located between 0 and 33° E, while significant positive trends are observed to the east from 33° E. But it should be pointed out that some stations, such as Slough or Lycksele, demonstrate significant positive trends and they are located in the West European longitudinal sector.

To study this effect in more detail, the diurnal variation of the trends has been calculated for all ionosonde stations shown in Fig. 4 (those ones with available observations for the period 1965–1991) using Model 2. The results are presented in Fig. 5. Stations have been separated according to their longitude. Whereas most of the analysed stations located in the 0–22° E longitudinal sector have negative trends (Fig. 5, top), those with $\lambda > 37°$ E (bottom panel) present significant positive trends for all SLT. Stations in the boundary region (middle panel) show small positive or negative trends which are not significant. A similar longitudinal effect was found earlier by Bremer (1998). It should be stressed that although we observe some stations with significant negative trends (all located in a small longitudinal sector of western Europe), they are a minority as most of the stations are seen to present positive trends (see Tables 2 and 3). This longitudinal effect also requires physical interpretation.

Another point which should be taken into account in the long-term trends analysis is the possible influence of the hysteresis effect. Similar to *fo*F2, the $M(3000)$F2 values also demonstrate a hysteresis effect in their solar cycle variations (Rao and Rao, 1969). As *hm*F2 values are derived from $M(3000)$F2, some effect may also be expected in the *hm*F2 variations as well. Danilov and Mikhailov (1999) and Mikhailov and Marin (2000) found in their *fo*F2 long-term trends research that only when the hysteresis effect at the rising and falling phases of a solar cycle was avoided, was it possible to obtain stable significant trends. They recommended using a selection of years around solar cycle maximum and minimum for the *fo*F2 trends analysis. Taking into account this result, we have tried to check the effect of the year selection on the resultant *hm*F2 trends. By analogy with the *fo*F2 trends analysis, we considered all years and then only years around the solar cycle extrema. The results of this comparison are given in Table 4 (Model 1) and in Table 5 (Model 2). The selection of years applied in this analysis is based on the observed annual mean R_{12} variations. Two or three years around solar cycle maxima (M) and minima (m) with close annual mean R_{12} values are selected for each solar cycle (Table 1). As it can be seen from Tables 4 and 5, although there are some small differences in the *hm*F2 slopes for the two selections of years, the character of the trends does not change. Therefore, this (M)+(m) selection of years does not help to reveal *hm*F2 trends, as it did in the case of the *fo*F2 trends. There is still no explanation for this result. Therefore, to reveal *hm*F2 long-term trends, all years with available observations are used (as done in Table 2) since this increases the statistics and the confidence of results obtained.

5 Discussion

The physical mechanism of the ionospheric trends remains still unclear. Although the thermosphere cooling due to an increase in the atmospheric greenhouse gases has been proposed by different researchers as an explanation for *hm*F2 long-term trends, the results of the F2-layer parameter trends analysis cannot be explained by this greenhouse hypothesis. Global cooling of the upper atmosphere due to this effect would result in a negative *hm*F2 trend (Bremer, 1992; Ulich and Turunen, 1997) and a positive one in *fo*F2 at least for the midlatitude F2-layer (Mikhailov and Marin, 2000), which is contrary to the obtained observations. This conclusion was obtained for the Northern Hemisphere stations. Long-term *hm*F2 trends for the Southern Hemisphere stations of the Ar-

Table 3. Number of stations with significant (positive and negative) *hm*F2 trends taking into account the results presented in Table 2. Confidence level of 95% is applied

Number of analysed Stations	0 SLT Model 1	0 SLT Model 2	6 SLT Model 1	6 SLT Model 2	12 SLT Model 1	12 SLT Model 2	18 SLT Model 1	18 SLT Model 2
27	19 sig. 16 posit. 3 negat.	13 sig. 6 posit. 7 negat.	20 sig. 19 posit. 1 negat.	17 sig. 12 posit. 5 negat.	19 sig. 14 posit. 5 negat.	18 sig. 13 posit. 5 negat	20 sig. 17 posit. 3 negat	18 sig. 14 posit. 4 negat.

Table 4. Calculated annual mean slope K (in 10–4 units) for the period 1965–1991. Regression of *hm*F2 with R_{12} (Model 1), and all years as well as years around solar maximum and minimum (Mm years) are used to obtain *hm*F2 linear trends. Significant trends at a confidence level of 95% are denoted by an "s" after the value

STATION	0 SLT All years	0 SLT Mm years	6 SLT All years	6 SLT Mm years	12 SLT All years	12 SLT Mm years	18 SLT All years	18 SLT Mm years	Analysed Years
MURMANSK	−3.23	1.00	3.48	1.56	1.66	4.38	3.43	3.02	1965–91
SODANKYLA	−6.71 s	−10.03 s	8.24 s	6.43 s	5.08	5.75	1.04	0.48	1965–91
LYCKSELE	18.98 s	20.27 s	24.26 s	24.85 s	25.22 s	30.6 s	22.41 s	23.11 s	1965–91
ARKHANGELSK	−2.36	5.39	8.95 s	13.46 s	4.77	7.56	15.08 s	16.37 s	1970–89
UPPSALA	−15.49 s	−8.67	−0.11	3.53	−13.42 s	−7.68	−19.85 s	−16.08 s	1965–91
ST PETERSBURG	7.64 s	11.23 s	17.87 s	15.84 s	10.12 s	13.03 s	13.54 s	13.71 s	1965–91
JULIUSRUH	−3.48	0.33	2.67	4.94	3.63	8.23 s	−0.19	2.95	1965–91
SLOUGH	9.19 s	13.05 s	23.78 s	22.55 s	15.00 s	15.46 s	15.66 s	18.56 s	1965–91
KALININGRAD	14.06 s	14.07 s	22.75 s	17.98 s	4.91	5.10	5.55	5.46	1965–91
DOURBES	−0.86	−1.01	−2.71	−1.23	−13.36 s	−6.26 s	−23.75 s	−19.91 s	1965–91
YAKUTSK	19.55 s	16.8 s	22.66 s	18.19 s	15.96 s	16.41 s	18.37 s	16.97 s	1965–90
TUNGUSKA	9.7 s	13.08 s	4.64	3.76	16.64 s	19.02 s	12.77 s	13.79 s	1969–91
MOSCOW	27.8 s	36.89 s	31.87 s	40.79 s	29.26 s	42.6 s	31.18 s	41.81s	1965–91
MAGADAN	9.29 s	10.42 s	9.02	10.39 s	−9.52 s	−2.63	3.19	2.54	1969–91
GORKY	0.69	2.29	8.77 s	7.01	15.47 s	16.7 s	14.58 s	15.35 s	1965–88
POITIERS	−4.43	−0.71	−6.09 s	−2.34	−7.59 s	−2.00	−2.19	7.19	1965–91
EKATERINBURG	15.75 s	16.84 s	30.87 s	32.35 s	14.87 s	18.29 s	22.15 s	25.2 s	1965–91
KIEV	8.89 s	12.58 s	13.75 s	17.69 s	4.35	6.35	9.82 s	11.24 s	1965–91
TOMSK	23.45 s	20.01 s	22.48 s	19.26 s	23.17 s	22.37 s	21.26 s	20.27 s	1965–91
BEKESCSABA	−11.94 s	−9.58 s	−3.77	0.58	−9.8 s	−6.77 s	−9.39 s	−6.23 s	1965–91
NOVOSIBIRSK	7.96 s	9.78 s	8.17 s	7.80	7.59 s	12.06 s	6.2 s	9.6 s	1965–91
IRKUTSK	11.13 s	8.54 s	17.43 s	10.74 s	15.92 s	12.01 s	16.62 s	11.32 s	1965–91
KHABAROVSK	10.27 s	10.93 s	22.89 s	2.77 s	13.48 s	7.66 s	14.63 s	12.48 s	1965–91
NOVOKAZILINSK	1.44	1.38	15.07 s	13.72	−0.97	−1.10	6.39	10.27	1965–88
ALMA ATA	12.51 s	15.12 s	28.27 s	29.71 s	18.77 s	20.99 s	22.98 s	25.81 s	1965–88
TASHKENT	4.99	5.93	10.98 s	5.52	3.97	3.02	9.37 s	6.53	1965–91
ASHKHABAD	33.41 s	32.32 s	40.78 s	37.79 s	35.22 s	35.04 s	41.44 s	41.35 s	1965–91

gentine Islands and Port Stanley were analysed by Jarvis et al. (1998) and for the Concepcion station by Foppiano et al (1999). Primarily negative *hm*F2 trends were revealed at these stations, especially for Port Stanley. The *hm*F2 observations from the first two stations were analysed by Danilov and Mikhailov (2001) using the same approach applied in this paper to reveal the trends. The Argentine Islands data are shown to demonstrate primarily positive *hm*F2 trends similar to most of the Northern Hemisphere stations, whereas at Port Stanley, there is a stable negative *hm*F2 trend around the clock. It was concluded that the difference might be due to the fact that Port Stanley is close to the region of the South-Atlantic Geomagnetic Anomaly where processes of direct corpuscular ionisation may play some role in the F2 layer formation thus disturbing the "normal" picture of *hm*F2 behaviour. A similar effect with negative *hm*F2 trends during nighttime hours takes place at Sodankyla which may be attributed to the F-region ionization by the soft electron precipitation (Mikhailov and Marin, 2001). Concepcion is a low-latitude station ($\Phi = -25.1$) located at the poleward slope of the equatorial anomaly bulge where F2-layer formation is strongly controlled both by thermospheric winds and plasma influx due to the "fountain" effect. Therefore, a special analysis is required to estimate the contribution of winds and equatorial electric fields to the formation of *hm*F2 trends at this station. Similar to other trend researchers, Fop-

Table 5. Calculated annual mean slope K (in 10^{-4} units) for the whole period with hmF2 observations available on a particular ionosonde station. Regression of hmF2 with $R_{12} + Ap_{12}$ (Model 2) , and all years as well as years around solar maximum and minimum (Mm years) are used to obtain hmF2 linear trends. Significant trends at a confidence level of 95% are denoted by an "s" after the value

STATION	0 SLT All years	0 SLT Mm years	6 SLT All years	6 SLT Mm years	12 SLT All years	12 SLT Mm years	18 SLT All years	18 SLT Mm years	Analysed Years
MURMANSK	−2.15	−0.68	−6.89 s	−4.97	−3.23 s	−0.98	−3.12 s	−1.25	1958–93
SODANKYLA	−10.63 s	−9.55 s	2.26 s	−1.16	−1.39	−2.68	−8.16 s	−9.8 s	1958–97
LYCKSELE	0.98	2.66	−0.05	3.06	1.23	3.52	−2.77	−2.49	1958–97
ARKHANGELSK	−5.31	−0.14	6.15 s	8.25	−0.28	−1.79	11.43 s	9.48 s	1970–89
UPPSALA	−2.79	−1.22	0.07	1.80	1.79	3.97	−3.01	−3.39	1958–97
ST PETERSBURG	3.15 s	3.13	5.84 s	4.50	0.32	3.99	2.26	3.38	1958–95
JULIUSRUH	−5.82 s	−5.96 s	−3.07 s	−1.32	−2.05	0.94	−4.18 s	−3.16	1958–91
SLOUGH	−4.49 s	−4.07	1.19	−2.3	0.63	−1.31	0.59	−0.12	1958–96
KALININGRAD	−1.18	−1.56	8.44 s	2.52	−2.95	−4.33	−3.08	−3.03	1965–93
DOURBES	−2 s	−2.72 s	0.13	−0.22	0.56	−0.33	−2.92	−2.90	1958–96
YAKUTSK	3.29	4.72	3.16	5.70	−0.04	3.81	3.01	5.69 s	1958–90
TUNGUSKA	3.29	5.93 s	1.93	0.19	11.08 s	12.12 s	6.01 s	8.04 s	1969–96
MOSCOW	19.79 s	17.28 s	21.82 s	19.58 s	24 s	25.88 s	23.74 s	22.15 s	1958–95
MAGADAN	−0.07	−0.72	−0.13	−3.17	−15.74 s	−9.89 s	−4.91	−6.95	1969–93
GORKY	−4.15 s	−6.23	3.35	−0.36	8.83 s	6.86	9.42 s	6.02	1959–88
POITIERS	−2.36	−1.89	−9.19 s	−4.58	−8.92 s	−4.36	−0.93	3.30	1958–95
EKATERINBURG	9.79 s	3.65	18.21 s	16.46 s	14.71 s	12.01 s	19 s	16.44 s	1958–94
KIEV	0.41	2.81	5.37	8.06	0.64	2.08	4.93	5.65	1965–91
TOMSK	4.81 s	2.68	5.22 s	3.80	4.86 s	4.73 s	5.24 s	4.9 s	1958–96
BEKESCSABA	−15.29 s	−11.48 s	−4.54 s	−2.70	−11.44 s	−6.83 s	−10.26 s	−5.44	1965–92
NOVOSIBIRSK	−3.41 s	−3.90	−4.39 s	−4.13	0.80	2.03	−1.96	0.07	1959–92
IRKUTSK	−4.45 s	−4.20	−2.99	−3.28	1.62	1.59	1.76	1.59	1959–91
KHABAROVSK	9.08 s	2.79	8.25 s	4.09	11.55 s	1.58	14.64 s	4.56	1960–92
NOVOKAZILINSK	−5.12	−5.41	5.19	3.59	−7.44 s	−7.87	2.17	5.96	1965–88
ALMA ATA	7.1 s	7.76 s	19.7 s	20.51 s	13.28 s	15.62 s	18.98 s	19.94 s	1958–88
TASHKENT	1.74	4.10	5.73 s	2.87	5.17 s	5.80	6.95 s	6.31	1962–92
ASHKHABAD	10.01 s	10.11 s	17.07 s	12.94 s	15.99 s	13.67 s	18.01 s	14.14 s	1958–97

piano et al. (1999) have analysed all available (1958–1994) observations which belong to different periods in the geomagnetic activity long-term variation and this cannot be ignored in the F2-layer parameters trend analysis (Mikhailov and Marin, 2000, 2001). In addition, it should be stressed that mechanisms of F2-layer trends are different at low, middle and high-latitude stations, reflecting the specificity of the F2-layer formation and they can hardly be attributed just to the thermosphere cooling due to the greenhouse effect.

In connection with this discussion it is interesting to consider the results by Keating et al. (2000) who, in analysing the orbits of 5 satellites, found a $9.8 \pm 2.5\%$ decrease in the total thermospheric density ρ at 350 km in 1996 with respect to 1976. They attribute this effect to a 10% increase in the atmospheric CO_2 abundance. According to their estimates, such a 10% decrease in ρ should result in a 5 km lowering of the constant pressure level. This seems to be in line with the hmF2 long-term decrease which many researchers are looking for. The Keating et al. (2000) results may be considered as the first and the only direct experimental evidence for long-term changes in the thermosphere presumably related with the greenhouse thermosphere cooling hypothesis. But one should keep in mind that such small (less than 10% over 20 years) changes in ρ may be due to some other reasons, such as: the conversion of orbital data to atmospheric density, the accuracy of the empirical model MET99 used for the data reduction. Unfortunately ionospheric F2layer observations cannot help us to reveal such small changes in ρ which (if they really exist) are masked by stronger processes. On the other hand, according to the geomagnetic control concept by Mikhailov and Marin (2000), the 1996 belongs to the period of decreasing geomagnetic activity (1990-91 is a turning point), therefore one should expect negative hmF2 trend at mid-latitudes after 1991 which is due to a decrease in geomagnetic activity but not to a greenhouse effect. Some examples of such change in the hmF2 trends after 1991 are given in Fig. 6.

This explanation for the F2-layer parameter long-term trends, which are not of the man-made origin, is related to long-term changes in geomagnetic activity. It was shown that the observed foF2 trends could be explained by an increase in the F2-layer storm activity as a result of the increasing geomagnetic activity. Moreover, the sign of the detected trends was shown to be different for the period prior to and after 1965, in accordance with the change in the smoothed variation of geomagnetic activity (1965 is another turning point). Therefore, trends should be analysed over a time interval which does not include different (increasing/decreasing) periods in geomagnetic activity. This was the reason for analysing the *hm*F2 trends for the time period 1965–1991 with the increasing geomagnetic activity. Such proposed geomagnetic control of the *fo*F2 trends implies corresponding trends in *hm*F2. So let us analyse *hm*F2 trends from this point of view. An approximate expression for *hm*F2 can be written for the day-time mid-latitude F2-region according to Ivanov-Kholodny and Mikhailov (1986):

$$h_m \cong \frac{H}{3}\{\ln[\mathrm{O}]_1 + \ln\beta_1 + \ln(H^2/0.54d)\} + cW, \qquad (2)$$

where $H = kT_n/mg$ is the scale height and [O] is the concentration of atomic oxygen, β is the linear loss coefficient at a fixed height h_1, W (in m/s) is the vertical plasma drift which is primarily related to thermospheric winds, c is a coefficient close to unity, $d = 1.38{*}10^{19}{*}(T_n/1000)^{0.5}$ is a coefficient in the expression for the ambipolar diffusion coefficient $D = d/[\mathrm{O}]$. The loss coefficient β depends on the density of the molecular gases N_2 and O_2: $\beta = k_1[\mathrm{N_2}]+k_2[\mathrm{O_2}]$, where k_1 and k_2 are the reaction rate constants of the two processes controlling the sink of O^+ ions in the F2-region:

$$\mathrm{O^+} + \mathrm{N_2} \xrightarrow{k_1} \mathrm{NO^+} + \mathrm{N}; \qquad \mathrm{O^+} + \mathrm{O_2} \xrightarrow{k_2} \mathrm{O_2^+} + \mathrm{O}$$

both rate constants being temperature dependent (Hierl et al., 1997).

The main processes responsible for the F2-layer storm effects are known: neutral composition, temperature and thermospheric wind changes at middle and lower latitudes, while electric fields and particle precipitation strongly affect the high-latitude F2-region (Prölss, 1995, and references therein). During geomagnetic disturbed periods, the high-latitude energy inputs (Joule heating and particle precipitation) cause changes in the thermosphere global circulation. These result in a perturbation of neutral composition and temperature, with a decrease in [O] and an increase in [N_2], [O_2] and neutral temperature. Such perturbations are believed to be the main reason for the mid-latitude F2-region negative storm effect. They result in an increase of the linear loss coefficient β (due to the N_2 and O_2 concentrations and temperature increase) with a corresponding *hm*F2 increase. The decrease in atomic oxygen concentration has an opposite effect on *hm*F2, but the effect of a β increase usually prevails (Mikhailov and Förster, 1997, 1999). Therefore, we should expect positive *hm*F2 trends at middle latitudes as a reaction to an increase in geomagnetic activity.

At lower latitudes, neutral composition variations are not large (e.g. Prölss, 1995 and references therein) and the usual observed positive F2-layer storm effects are primarily due to an increase in the equatorward thermospheric wind. Some contribution to the F2-layer positive storm effects at lower latitudes provides atomic oxygen (Mikhailov et al. 1995). This results in small or even positive *fo*F2 trends at lower latitudes, as was shown by Mikhailov and Marin (2000) and should result in positive *hm*F2 trends as well. As both mechanisms work in one direction (*hm*F2 increase), changing

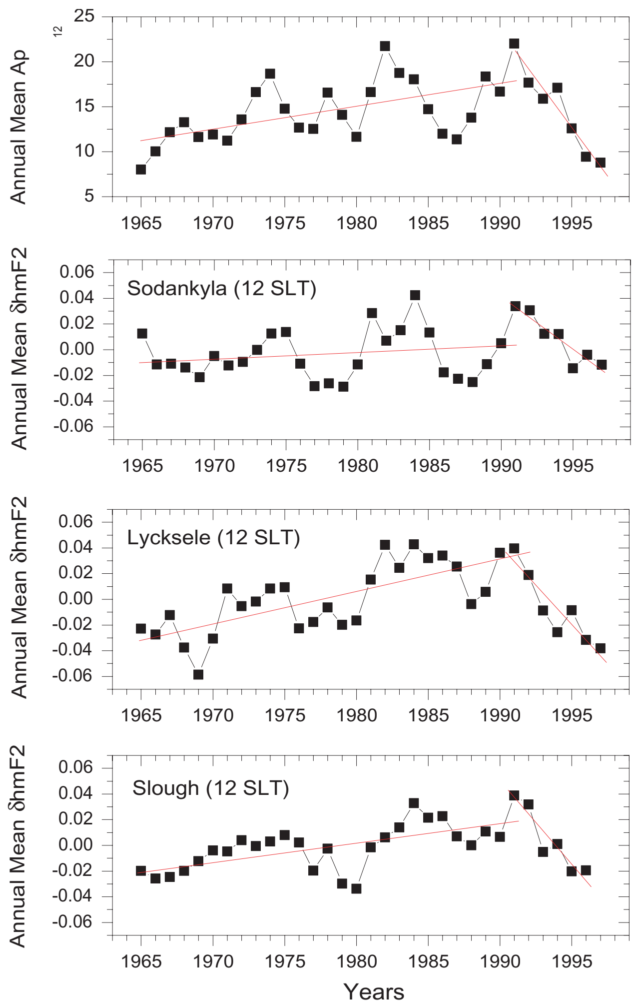

Fig. 6. Annual mean Ap_{12} and δhmF2 variations at Sodankyla, Lycksele and Slough, and 12 SLT (Model 1). Note different signs of trends for the period prior and after 1991.

each other as we pass from middle to lower latitudes, one should not expect any pronounced latitudinal dependence in *hm*F2 trends, as it was shown by our analysis. Therefore, the revealed positive *hm*F2 trends from the majority of the stations can be explained by the F2-layer storm mechanism due to the long-term increase in geomagnetic activity which takes place after 1965.

Some of the stations located in the same longitudinal sector (western region of Europe) have been found to present negative trends. These trends cannot be explained by the geomagnetic hypothesis and they require an additional analysis. This may be due to the low quality of *hm*F2 data. It should be stressed that *hm*F2 values were derived from M(3000)F2 by using an empirical formula which inserts an additional noise to the analysis and, therefore, *hm*F2 trend results are not as reliable as *fo*F2 ones. Ionospheric trend analysis is a very delicate procedure and an inclusion of some erroneous points may seriously affect the K value. This is really strange when close stations demonstrate *hm*F2 trends of different signs.

Table 6. Calculated coefficients of correlation r between annual mean hmF2 and Ap_{12} values for the whole period with hmF2 observations available on a particular ionosonde station. Regression of hmF2 with R_{12} (Model 1) and with $R_{12} + Ap_{12}$ (Model 2), and all years in the indicated period are used to obtain the coefficients. Significant coefficients at a confidence level of 95% are denoted by "s" after the value

STATION	0 SLT Model 1	0 SLT Model 2	12 SLT Model 1	12 SLT Model 2	Analysed Years
MURMANSK	0.157	−0.008	0.449 s	0.054	1958–93
SODANKYLA	0.011	−0.006	0.525 s	−0.003	1958–97
LYCKSELE	0.509 s	0.040	0.476 s	0.038	1958–97
ARKHANGELSK	0.490 s	−0.021	0.819 s	−0.017	1970–89
UPPSALA	0.164	−0.004	0.236	−0.008	1958–97
ST PETERSBURG	0.608 s	0.053	0.389 s	0.029	1958–95
JULIUSRUH	0.576 s	−0.040	0.579 s	0.020	1958–91
SLOUGH	0.624 s	−0.007	0.587 s	−0.004	1958–96
KALININGRAD	0.683 s	0.039	0.496 s	0.036	1965–93
DOURBES	0.274	−0.075	−0.096	−0.037	1958–96
YAKUTSK	0.597 s	0.038	0.670 s	0.074	1958–90
TUNGUSKA	0.687 s	0.053	0.569 s	0.073	1969–96
MOSCOW	0.512 s	0.030	0.383 s	0.024	1958–95
MAGADAN	0.627 s	0.023	0.386 s	0.020	1969–93
GORKY	0.312	−0.082	0.509 s	−0.023	1959–88
POITIERS	0.439 s	−0.018	0.162	−0.030	1958–95
EKATERINBURG	0.467 s	0.012	0.311	0.005	1958–94
KIEV	0.672 s	0.012	0.307	0.021	1965–91
TOMSK	0.635 s	0.055	0.580 s	0.048	1958–96
BEKESCSABA	0.100	−0.015	0.008	−0.003	1965–92
NOVOSIBIRSK	0.648 s	−0.023	0.585 s	0.045	1959–92
IRKUTSK	0.548 s	0.019	0.517 s	0.044	1959–91
KHABAROVSK	0.404 s	0.025	0.338 s	0.011	1960–92
NOVOKAZILINSK	0.366	0.013	0.448 s	0.002	1965–88
ALMA ATA	0.547 s	0.041	0.202	0.029	1958–88
TASHKENT	0.230	−0.011	−0.143	−0.035	1962–92
ASHKHABAD	0.498 s	0.045	0.328 s	0.046	1958–97

An example of this fact can be observed when comparing Lycksele and Uppsala ionosonde stations. These stations are pretty close (see Table 2), but they demonstrate significant trends of different signs. Nonetheless, positive hmF2 trends obtained for most of the stations analysed may be considered as serious support for the geomagnetic origin of the F2-layer parameter long-term trends.

Finally, in order to test the proposed relationship between the hmF2 trends and geomagnetic activity, we calculated the correlation coefficients between the annual mean δhmF2 and the Ap_{12} for each ionosonde station, using the whole period with observations available. The results of this analysis are given in Table 6. All analysed stations demonstrate positive δhmF2–Ap_{12} correlation, with most of them (19 of 27 both at 00 and 12 SLT) being significant with a confidence level of 95% when Model 1 is used. Such correlation disappears when a geomagnetic index is included to the regression (Model 2) and this is not surprising. The obtained positive correlation (when Model 1 is used) may be considered as a clear indication of the relationship between hmF2 trends and geomagnetic activity. However, it should be pointed out that despite the fact that the δhmF2–Ap_{12} correlation disappears when Ap_{12} is taken into account in the regression (Model 2), the inclusion of this index, in fact, does not remove the geomagnetic effects on the trends (Mikhailov and Marin, 2000, 2001). Although there is an obvious relationship between the F2-layer parameter trends and the geomagnetic activity, it is impossible to remove this geomagnetic effect from the trends revealed using any conventional index (e.g. monthly or annual mean Ap) of geomagnetic activity. If it could be done using the conventional indices, the problem of the F2-layer storm description and prediction would have been solved long ago, but this is not the case up until now. This is not surprising as any global geomagnetic activity index cannot, in principle, take into account the whole complexity of F2-layer storm effects with positive and negative phases depending on season, UT and LT of storm onset, storm magnitude, etc. Indeed, the inclusion of Ap_{12} to the regression (Model 2) has some effect on the trend magnitude, but without changing, in principle, the results obtained when Ap_{12} was not considered (Model 1). It was shown that the majority of detected hmF2 trends were positive regardless of the model used (Table 3). Therefore, any interpretation of the F2-layer parameter trends should consider the geomagnetic effect as an inalienable part of the trends revealed and this can be done based on the contemporary understanding of the

F2-layer storm mechanisms. On the other hand an additional analysis is required to find out the reason for significant negative *hm*F2 trends revealed at some stations.

6 Conclusions

The main results of this analysis may be listed as follows:

1. The new approach proposed by Danilov and Mikhailov (1998, 1999) and Mikhailov and Marin (2000) has been used to reveal *hm*F2 linear trends at 27 European and Asian ionosonde stations. Although the choice of a simple formula by Shimazaki (1955) for the *hm*F2 derivation has no principle influence on the trends obtained during nighttime hours, the trends turn out to be slightly less if the effect of underlying ionisation is taken into account by applying more accurate formulas during daytime hours.

2. The majority of the stations show significant positive trends for the period of increasing geomagnetic activity 1965–1991, without any dependence on latitude (neither magnetic nor geographic). This result can be explained in the framework of the long-term increase in geomagnetic activity and related F2-layer storm activity. The significant positive correlation obtained between the annual δhmF2 and Ap_{12} values confirms this close relationship between *hm*F2 trends and geomagnetic activity. However, some stations located in the western part of Europe demonstrate significant negative trends. This longitudinal effect (earlier revealed by Bremer) needs further analysis as significant negative trends observed at some western European stations are not explained within the geomagnetic control concept.

3. Unlike the case with *fo*F2 trends, a selection of years around solar cycle minimum and maximum does not help to reveal *hm*F2 trends and using of all years with available observations may be recommended for the *hm*F2 trends analysis. This increases the statistics and the confidence of results obtained.

4. Positive significant *hm*F2 trends obtained for the majority of the stations considered (regardless of the model used) contradict the suggestion that thermospheric cooling due to the greenhouse effect might be the cause of the F2-layer parameter trends. However, they can be explained in the framework of the geomagnetic control hypothesis proposed by Mikhailov and Marin (2000).

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